Chapter 9
Concrete Quality Verification and Testing

9-1. Quality Verification

a. General. The construction quality verification system is necessary to assure the Government that the finished work complies with the plans and specifications. The inclusion of quality control requirements for the Contractor does not relieve the Contracting Officer of the responsibility for safeguarding the Government's interest. For civil works concrete construction, the resident engineer has the added responsibility for obtaining the quality of concrete in the various parts of the structure based on explicit instruction from the engineering division of the district office (see Chapter 6 of this manual). Depending on the scope of the work and the guide specification selected, the Government may or may not select the mixture proportions, but in all cases, the Contracting Officer is responsible for assuring that the strength and other requirements as set forth in the specifications or in the designer's instructions to the field personnel are met. The Contractor will mold, cure, and perform strength testing of concrete cylinders as part of his quality control program. The Government will perform compressive strength testing as part of the quality assurance program. In case of arch dams, all strength testing will be molded, cured, and performed by the Government. The budget for these GQA responsibilities should be included in the Project Management Plan. Details of requirements and procedures for CQC and GQA are specified in ER 1180-1-6, "Construction Quality Management," which contains detailed requirements for controlling projects with prescriptive specifications such as the mass-concrete specification. The GQA responsibility is not to be imposed on the construction contractor. If personnel shortages preclude the use of government personnel to accomplish GQA, it should be done by a commercial testing organization under contract to the Government.

b. Government quality assurance. During the construction stage, the Contracting Officer, through his authorized representatives, which include the resident engineer and his staff, is responsible for acceptance testing and quality verification to enforce all specification requirements and for monitoring the Contractor's quality control operations. These functions include but are not limited to: verification of all operations for compliance with specifications, reviewing and, when required, approving contractor submittals including certificates of compliance and contractor-developed mixture proportions. If acceptance testing of cement, pozzolan, slag, admixtures, or curing compounds are required, the resident engineer is responsible for making the necessary arrangements for such tests with the appropriate division laboratory, or in the case of cement, pozzolan or GGBF slag, with WES. The resident engineer is responsible for requesting the division laboratory to verify the quality of the government project laboratory, any commercial laboratories operating under contract to the Government and the contractor's quality control laboratory as required by ER 1110-1-261, "Quality Assurance of Laboratory Testing Procedures."

(1) Quality assurance representative. This individual may be a government employee or may be an employee of a private engineering firm under contract to the Government and not affiliated with the construction contractor. He is the key figure in the operations attendant to concrete quality assurance. The effectiveness of the quality verification operation in assuring uniformity of the concrete and in obtaining compliance with specification requirements depends to a large degree on the thoroughness with which the quality assurance representative is instructed and trained in the performance of his duties. While it is expected that the quality assurance representative will have knowledge of the basic requirements for the production of concrete of high quality, it is nevertheless necessary to instruct him in the details of quality verification as they apply to each specific project. This should be accomplished through training conferences together with written guides and instructions prepared by the government concrete engineer and his shift supervisors or by the project engineer on smaller projects. Previous experience on similar work is highly desirable. Previous experience cannot entirely compensate, however, for proper instruction and training of quality assurance representatives in the duties unique to a particular project. These representatives should be assigned to a project prior to completion of the contractor's concrete plant. Preferably, they should be trained for duty on a particular project as the concrete plant is being erected so that they may become thoroughly familiar with the plant and particularly those aspects of the equipment bearing on the quality verification procedures. For example, on a large concrete project the mixing plant quality assurance representative should become familiar with the mixing plant and all of its operating features. All persons assigned as quality assurance representatives should be certified by ACI or have equivalent training. EP 415-1-261 provides detailed responsibilities and a check list for the GQA representative.

(2) Testing technicians. Technicians, either government employees or employees of a private engineering firm contracted by the Government, are responsible for the quality assurance testing to verify the Contractor's quality control tests and for acceptance testing of the concrete. They are also responsible for obtaining

samples of materials for other laboratories. All work done by technicians must be done in strict accordance with applicable standards to ensure the validity and acceptance of test results. Certification of concrete technicians is provided by ACI. This certification can be obtained by completing a 3- or 4-day course offered by ACI at announced times in many of the major cities of the country or by completing the Concrete Technicians Course at WES. All persons assigned as concrete technicians and responsible for quality assurance testing should be certified by ACI or have equivalent training.

(3) Organization.

(a) General. The Government's quality assurance organization must be flexible to allow for changes in rates of placement as construction progresses. In general, the following organizations should be provided by the Government to satisfy the area/resident engineer's responsibility for acceptance testing and quality verification to enforce all specification requirements and for monitoring the contractor's quality-control operations.

(b) Major concrete project. On large concrete projects, the organization should have a materials engineer (or technician) reporting directly to the resident engineer and being responsible for all phases of quality assurance from aggregate production through curing and protection of the concrete. The organization should include a shift supervisor (quality assurance representative) for each shift. Under each shift supervisor, the organization should include one placing quality assurance representative for each location at which concrete is being placed, one mixing plant quality assurance representative, and one quality assurance representative assigned to verification of cleanup, curing, protection, and finishing. The organization should include a laboratory technician and assistants as required to handle acceptance testing of aggregates and concrete, to consolidate reports, prepare summary reports, and keep records. The laboratory technician should report directly to the materials engineer. On a very large project, several contracts on the same project may be supervised by a single area engineer. Under such circumstances, the engineer reports to the resident engineer and supervises all concrete activity on the project. The quality assurance force required for aggregate quality verification depends upon job conditions. Where the Contractor's quality control has been proven satisfactory, sampling should be required only at the point of acceptance (mixing plant) and the quality verification should consist only of routine observation of plant operations; this work can be handled jointly by the shift supervisors and the engineers or by special assignment. Usually quality verification of aggregate processing operations does not require continuous assignment of personnel.

(c) Moderate concrete volume. For smaller projects, it is necessary to modify the organization to suit the project conditions. In most instances, quality assurance representatives are required to serve in dual capacities, shifting from quality verification of concrete mixing and placing to other phases of the work as required. Quality assurance representatives may also be required to verify curing, protection, and cleanup. It is desirable to have continuous quality verification of batching and mixing operations.

(d) Ready-mix operations. When concrete is centrally mixed at the plant, a quality assurance representative should be on duty full time at the plant where he can observe and test the mixed concrete and can reject concrete which fails to meet job requirements. When concrete is transit-mixed, full-time plant quality verification is desirable, but primary responsibility for acceptance of concrete belongs to the quality assurance representative at the site of the work. If full-time plant quality verification is not possible, the plant should be visited frequently to ensure that batching is carried out properly.

(e) Small job. There is a tendency to overlook small jobs and the small parts of large jobs. Frequently, small structures such as curbs and sidewalks have very severe exposure and require concrete of high durability. Although a quality assurance representative on a small job may have duties other than concrete quality verification, no concrete placing should be started without a quality assurance representative on hand.

(4) Records. The value of clear, concise, and complete records is sometimes overlooked during the construction of a project. In devising a system of reports, and preparing forms for these reports, it should be realized that these reports will constitute a part of the official record of the construction operations and may be the sole source of reliable information on the procedure, practices, and results obtained during construction. Reports in various forms should be made daily and at other stated intervals for several purposes. Standard forms are available for reporting most test results. Where necessary, special forms may be devised on the project to suit project requirements. Reports will supply information on, and preserve as a permanent record, facts concerning progress of the work, factors affecting progress, instructions given to contractors, samples secured, tests made, and any other necessary data. Unusual occurrences in the plant may be noted on the recorder chart by the quality assurance representative or plant operator.

The information should ultimately appear in a report. The reports made by placing quality assurance representatives and quality assurance representatives engaged on cleanup, curing, finishing, and protection should follow a well-devised standard form on which the essential facts are recorded for the period of quality verification. Government test results should include control charts and variability of the material tested. Each such report form should also provide space for recording unusual happenings and for any pertinent remarks concerning shift operations.

9-2. Required Sampling and Testing for CQC and GQA

The following tests are normally required for a major civil works concrete construction project for CQC and GQA purposes. The procedures and frequencies of all the necessary CQC tests should be included in the contract specification. Tests for GQA are at the Government's discretion and should not be specified in the specification except those cases where sampling and facility are the Contractor's responsibility. The required frequencies for GQA and government acceptance tests should be included in the Engineering Considerations and Instructions to Field Personnel for each project. The recommended testing frequencies for GQA are listed in the following paragraphs.

a. Aggregate grading. In order to determine compliance with the specification requirement that aggregates must be within certain grading limits as delivered to the mixers, samples must be obtained as delivered to the mixer. On mass concrete projects containing 150-mm (6-in.) NMSA, the specifications require that an automatic small screening plant be included in the batch plant. On concrete projects containing 75-mm (3-in.) NMSA, a cost analysis should be made before specifying the automatic screening plant. The automatic screening plant makes use of angled quarry screens, which by their nature are 80-percent efficient at the best and cannot be compared directly to Gilson screens, which are 95- to 98-percent efficient. The automatic screening plant must contain controls to vary the angle and frequency (vibrations per minute) of each individual screen. Optimum loading, screen angle, and frequency of each screen must be established by the Contractor before construction begins. Correlation tests with Gilson sieving equipment must be performed before construction and every 60 days while concrete production continues. The quarry screens on the automatic screening plant will normally require a larger screen than the Gilson screens for comparable results. With such a device, the sampling, screening, determination of mass, and disposal is accomplished automatically. Normally, it is not necessary to procure samples at any other location. Samples may be procured at any point in the production line where it is deemed necessary. Where 150-mm (6-in.) NMSA is used, it might not be feasible to sample the 75- to 150-mm (3- to 6-in.) fraction from the weigh batcher. Then samples may be obtained from the conveyor belt or other convenient place as close as possible to the end of the handling operations. When sampled from a conveyor belt, the belt should be stopped, and the sample should consist of a complete section and not hand-picked from the top. Where aggregates are supplied by a commercial producer located some distance from the project, sampling for acceptance tests will not be made at the producer's plant. Such tests would not reflect the possible effects of segregation in stockpiling at the project and breakage in handling.

(1) Frequency.

(a) On-site plant. During each 8-hr shift when concrete is being produced, at least one sample of each size of aggregate should be taken. During the early stage of a large project, several samples per shift should be tested until the production control has achieved uniformity. After 1 month, if the Contractor's control testing has proven to be satisfactory, frequency of government sampling may be reduced to one-third of that stated above.

(b) Off-site commercial plant. The frequency of QA testing of the aggregate grading at an offsite commercial plant will vary somewhat with the quantity of concrete and the rate of concrete usage from that plant where concrete is supplied to many customers and the concrete mixture is furnished by the contractor. For minor concrete jobs, the aggregate should be tested before concrete placing begins and once per week while concrete is being placed. On larger structural concrete jobs, the aggregate grading should be tested by the GQA representative before start of concrete placement and at least twice per week thereafter while concrete is being placed.

(2) Size of samples. Sample sizes for sieve analysis are given in ASTM C 136 (CRD-C 103). For fine aggregates and finer sizes of coarse aggregate, samples obtained in accordance with CRD-C 100 may be reduced in size by a sample splitter or by carefully following instructions for quartering given in ASTM C 702 (CRD-C 118). For aggregate sizes smaller than 37.5 mm (1-1/2 in.), the required sample sizes are sufficiently large in relation to individual particle size so that compliance with the grading specification may be fairly determined by a single test. For 37.5 mm (1-1/2-in.) and larger sizes, however, this is not true. While sample sizes given in ASTM C 136 (CRD-C 103) for nominal maximum aggregate sizes larger than 37.5 mm (1-1/2 in.) are practical for laboratory sieve

analysis testing equipment, the samples are subject to large random sampling errors. Therefore, compliance with specification should be determined from the average of five consecutive tests. Whenever a single test result shows a major deviation from specification requirements, the frequency of sampling and testing should be accelerated to as great an extent as practical until it is established whether the indicated noncompliance was the result of sampling error or the result of an actual deficiency in the aggregate processing equipment. Sometimes a single retest will be sufficient to establish the cause of the noncompliance. If sampling and testing equipment is installed that is capable of handling specimens five times as large as those required by ASTM C 136, averaging of test results is not necessary.

b. Aggregate quality - large project. Paragraph 7-1 requires initial testing of the Contractor's chosen aggregate sources to confirm that the aggregate quality has not changed since it was tested in the design stage and to confirm that it meets aggregate quality specification requirements. Quality testing by the Government should be performed during the life of the contract at about 10 percent of the rate listed in the CQC requirements of the specifications. Tests performed by the Contractor under CQC should be monitored carefully by the GQA representative. Experience has shown that quality of aggregate can change, either gradually, or at times dramatically as production proceeds laterally and vertically in the source. Failing quality tests will require additional testing by the Contractor and by the Government. Resident office personnel should record and monitor the location in the quarry or pit from which the aggregate is being produced. A change in visual appearance or quality test results could signal a change in production location at the source.

c. Free moisture on aggregates. Adjustments of batch weights to compensate for variation in aggregate moisture is a basic contractor responsibility. The Contractor's methods for complying with this requirement should be reviewed and verified at least once weekly. Whenever the concrete is considered out of control due to slump or air content, the government testing should increase in a cooperative effort with the Contractor in obtaining testing information needed to perform the necessary adjustments. When a moisture meter is required by the specifications, its accuracy should be verified at least once per week.

d. Slump and air content. The slump test ASTM C 143 (CRD-C 5) is made as a check on the uniformity of the concrete and to determine whether the concrete being sent to the forms is placable. Samples for slump and air content tests may be taken and tested at the batch plant for onsite plants; however, the required slump and air content is that required at the placement. If slump or air content loss is experienced, then occasional tests must be performed at the placement site to determine amount of slump loss or air content loss. In that case, slightly higher values may be adopted for use at the plant, so that the proper slump and air are obtained at the placement. Considerable slump loss and air content loss are usually associated with conveying or pumping concrete considerable distances. Correlation test samples for compressive strength is also necessary when considerable slump and air content loss is experienced. Variation in slump is caused chiefly by variation in aggregate moisture and air content. Whenever either or both of these factors vary, slump tests should be made as frequently as needed to ensure that the concrete is of the required consistency. When the mixture is of the required consistency, slump tests should be made at least twice per shift for each concrete mixture being placed. Control of air content is essential to the placeability and the durability of concrete. When no control problems are encountered, the air content should be determined at least twice per shift for each concrete mixture being placed. When the concrete contains a fly ash with a variable carbon content, the testing rate should be increased. After 3 months, if the Contractor's control has been adequate, slump and air content need to be measured by the Government only when cylinders are fabricated.

e. Concrete temperature. The temperature of cooled concrete should not be measured until 20 minutes after mixing. If the largest aggregate was cooled for an insufficient period of time, the particles may be only surface cooled. If so, this fact will be reflected in the delayed temperature reading. The sensing element of the thermometer should be at least 3 in. below the surface of the fresh concrete when the measurement is made. The temperature of each concrete mixture should be checked twice per shift when concrete is being placed.

f. Compressive strength.

(1) Purpose. Strength tests are performed for different purposes depending on the type of construction and the specification used. For mass-concrete structures where mixture proportioning is provided by the Government, strength tests are needed to measure the variability of the concrete mixture. In this case, strength is not necessarily the most critical factor concerning the concrete mixture. Other considerations, such as durability or thermal cracking, may dictate the w/c. Nevertheless, compressive strengths are good indications of variations in other concrete properties. For concrete structures where mixture

proportioning is the Contractor's responsibility, concrete strength is a part of the acceptance requirements. The strength criteria are normally determined by structural requirement.

(2) Testing responsibility. The specifications should require the Contractor to mold, protect, cure, and test compressive strength cylinders on all concrete construction where the Government furnishes the mixture proportions, except for arch dam construction where the Government will perform all the strength testing. The frequency of testing by the Contractor should be in accordance with paragraph 9-2f(4). In addition, the GQA representative should mold, cure, protect, and test at least 1 set of test cylinders for each 10 sets of cylinders made by the Contractor. The GQA test cylinders should be from the same batch of concrete as one of the CQC test cylinders. After a minimum of 30 sets of cylinders are tested, the resident engineer may choose to lower the amount of government-molded, -cured, and -tested cylinders to 5 percent (1 in 20) of the cylinders tested by the Contractor if the CQC tests are proven satisfactory. A 10-percent differential in the test results between CQC tests and GQA tests would be cause for further investigation of the Contractor's casting, curing, and testing procedures and equipment.

(3) Sampling plan. The frequency of sampling, number of cylinders made, and ages at which the cylinders are tested will vary with the type and size of the project. At the beginning of each project, a sampling plan will be developed by the Government that is consistent with the project specifications. The sampling plan should obtain information on the quality of each class of concrete at the least cost. The sampling plan must reflect the variability characteristics of heterogeneous concrete. The individual samples must be taken in such a manner that each sample is selected in an unbiased manner. The number of test specimens fabricated will depend on the number of ages at which they are to be tested. For part of the work, two specimens should be tested at the same age to derive the within-batch coefficient of variation. A test is defined as the average strength of all specimens of the same age, fabricated from a sample taken from a single batch of concrete. Samples should be obtained by means of a random sampling plan designed to minimize the possibility that choice will be exercised by the sampler. Probability sampling of materials is discussed in ASTM E 105 (CRD-C 579). This procedure should be used for guidance in developing a random sampling method. The sampling plan should also include the predetermined sampling location where representative samples will be obtained.

(4) Frequency and testing age. During the early stages of a project, it is desirable to increase the frequency of testing until control is established. Structural concrete should normally be sampled once per shift and mass concrete once per day for each concrete mixture placed. When mixture proportions are provided by a division laboratory, as would be the case of a large mass structure such as a lock or dam, accelerated strength testing should be used to control batching and mixing based on relationships developed by the laboratory. Two specimens will normally be molded and cured in accordance with ASTM C 684 (CRD-C 97), Method A. Where conditions are not suited to this method, Method B or C may be used. Laboratory mixture proportioning studies should be developed with the same method that will be used on the project. The design age should be decided by the designer depending on the type of structure involved, the types of cementitious materials and the loading conditions anticipated. As examples, the design age for a large lock or dam may be 180 days or even 1 year if design loadings are not likely to occur sooner. However, the design age for a bridge or pumping station will likely be 28 days and could possibly be shorter depending on the construction techniques used and the construction and in-service loadings anticipated. The information age could be selected to coincide with form-stripping schedules, removal of shoring, or in the absence of construction considerations at intervals such as 7, 14, or 28 days. In addition to control or acceptance cylinders, occasionally there will be a need for extra cylinders. With prestressed concrete, for example, when prestressing is to be applied when the concrete attains its loading strength, it will be necessary to test cylinders at various ages. Sometimes field-cured cylinders are used in determination of form removal time. A sampling plan guide for number and test age of cylinders is shown in Table 9-1.

(5) Sampling and testing methods. On all projects, concrete will be sampled in accordance with ASTM C 172 (CRD-C 4). The test specimens will be molded and cured in accordance with ASTM C 31 (CRD-C 11). When the nominal maximum size aggregate is larger than 50 mm (2 in.), the concrete sample shall be wet sieved in accordance with ASTM C 172 over a sieve having 50-mm (2-in.) square openings. Concrete test specimens will be tested in accordance with ASTM C 39 (CRD-C 14).

(6) Analysis of tests. Strength variation is the key consideration in analysis of data derived from tests of concrete cylinders. Because of this variation, statistical methods are used to analyze and present the numerical data. The magnitude of variations in the strength of concrete test specimens depends on how well the materials, concrete

Table 9-1
Number of Cylinders to Be Cast

	Number of Test Specimens at Various Ages		
Concrete Type	1 Day	Information Age(s)	Design Age
Structural & minor		1	2
Mass	2	1	2

manufacture, and testing are controlled. The strength results will vary above and below an average and fall into some probability distribution. The strength test results should be evaluated to determine the within-batch-coefficient of variation and overall standard deviation. ACI 214 provides details on these methods of analysis. The procedures involve mathematical computations which lend themselves to computer processing. There are many commercial programs available for this purpose. The selection of appropriate computer programs for evaluating test data may be made with the advice of CECW-EG. The standards for control are shown in Table 9-2 for 28-day strength results. The standards for accelerated strength test results will be developed by the division laboratory based on an analysis of 28-day strength results and the accelerated strength test results. After the first 30 test results are available on the project, they should be analyzed for average strength and standard deviation and the mixture proportions adjusted as appropriate.

(a) Within-test coefficient of variation. Within-test coefficient of variation is caused by fabricating, curing, and testing the cylinders. When the coefficient of variation is greater than 5.0 percent, the following procedures should be evaluated:

- Sampling procedures
- Fabrication techniques
- Handling and curing cylinders
- Quality of molds
- Variation in curing temperatures
- Variation in curing moisture
- Delays in transporting to the laboratory
- Size of the test specimens
- Capping procedures

(b) Overall standard deviation. Overall standard deviation is a term representing a value related to both within-test variation and batch-to-batch variation. The overall standard deviation is defined as the square root of the sum of squares of within-test and batch-to-batch standard deviations. The variation may be introduced by practices in proportioning, batching, mixing, and transporting concrete. When overall standard deviation is higher than 600 psi, the following procedures should be evaluated:

- Characteristics and properties of the ingredients
- Batching and mixing procedures
- Sampling procedures
- Causes for variation in w/c, such as aggregate moisture
- Causes for variation in water requirements

(7) Control criteria. On projects where mixture proportions were developed by the Contractor, the Contractor shall submit revised proportions when the compressive strength tests do not meet the specified criteria. On projects where mixture proportions were developed by a division laboratory, the area/resident engineer in concert with engineering division personnel should revise the proportions as necessary to meet the required average strength criteria. In both cases, adjustments to the procedures should be made after the first set of 30 tests if the overall standard deviation is approaching or beyond the limit of 600 psi.

(8) Prediction of later age strengths. Where possible, the division laboratory will develop an appropriate correlation of the relationship between accelerated tests and standard cured compression tests. At the start of concrete placement, testing should be performed at accelerated ages and later age. After the first 30 tests, the linear regression equation should be verified or reestablished. If there is a discrepancy between equations, the division laboratory should be consulted to analyze the data. As confidence is gained with predicting later age strength with the linear regression equation, the amount of later age testing may be reduced by as much as 50 percent.

Table 9-2
Standards of Control for Concrete Compressive Strength

Class of Operation	Standards for Concrete Control				
	Excellent	Very Good	Good	Fair	Poor
Within test, coefficient of variation, percent	0 - 3.0	3.0 - 4.0	4.0 - 5.0	5.0 - 6.0	Above 6.0
Overall standard deviation, psi	0 - 400	400 - 500	500 - 600	600 - 700	Above 700

9-3. Nondestructive Testing

a. General. Nondestructive testing of concrete as described herein includes methods of tests on concrete structures or structural members which do not reduce the functional capability of the structure, although some of the methods listed do require minor repairs if the concrete will be exposed to view. The tests described are those which are used to gain an indication of the quality of hardened concrete in place.

b. Policy. Nondestructive testing will not be used in lieu of compressive strength tests of cylinders, air content tests by the pressure method, slump tests, or any other test for the evaluation and acceptance of concrete placed on any civil works projects.

c. Applicability. Nondestructive tests may be used to locate areas of unsound concrete or concrete suspected of being significantly below the specified levels of strength required by the design or the required levels of durability. If areas are located where unsound, weak, or deteriorated concrete is likely, the condition of the concrete may be confirmed by coring unless the structure is so heavily reinforced that useful specimens cannot be obtained. Nondestructive testing may also be used to indicate changes with time in characteristics of concrete such as those caused by the hydration of cement so that it provides useful information in determining when forms and shoring may be removed.

d. Nondestructive testing methods. The methods discussed do not represent all the available methods but only those that have been standardized by ASTM. More detailed discussion of the advantages and limitations of these test methods is given in ACI 228.1R.

(1) Rebound hammer (ASTM C 805 (CRD-C 22)). The rebound hammer consists of a spring-loaded steel hammer which, when released, strikes a steel plunger in contact with the concrete surface, and rebounding indicates a rebound number on a calibrated scale. Only the concrete in the immediate vicinity of the plunger influences the rebound number; therefore, the test is sensitive to the local conditions where the test is performed. Because the rebound hammer tests only the near-surface layer of concrete, the rebound number may not be representative of the interior concrete. The probable accuracy in predicting concrete strength in a structure by this method is only ± 25 percent, so its use is clearly limited to attempting the differentiation between areas of large quality variation in the same structure. Closer accuracy can be obtained by calibrating the hammer with project concrete of known strength. The main advantage of the rebound hammer is its extreme portability so that many tests may be made easily in a short period of time.

(2) Penetration resistance (ASTM C 803 (CRD-C 59)). The penetration-resistance test uses a powder-driven stud to measure the penetration resistance of concrete. This test, like the rebound hammer, is a hardness tester; however, attempts continue to be made to correlate the penetration of the stud to concrete strength. The apparatus is easily portable, using a modified powder cartridge stud gun and studs or probes. The resulting damage to the concrete surface is minor and may be easily repaired. A large number of tests may be completed in a relatively short period of time. Attempts to correlate the penetration-resistance test results with core tests and cylinder tests

indicate coefficients of variation and range about 10 times as large as the core and cylinder test results. Therefore, the use of the this test should be limited to applications where large variations are suspected in the concrete quality or to determine the locations for borings.

(3) Cast-in-place pullout tests (ASTM C 900 (CRD-C 78)). Pullout tests use a hollow stem ram to pull a bolt with a washer on its lower end that has been cast in the concrete at the time of placement. The pullout assemblies are incorporated into the formwork for critical structural members. As an alternative, pullout assemblies may be cast into large blocks which are cast at the same time as the structural member and consolidated and cured in a similar way. The main advantage of the pullout tests is that it does produce a well-defined failure in the concrete and measures a static strength property of the concrete in a structure. The equipment is easily portable. The pullout strength does correlate with compressive strength; however, the coefficient of variation of pullout test results has been found to be approximately 7 to 10 percent. This is about two to three times greater than that of standard compressive strength tests. The main limitations are that the test locations are fixed at the time of placement which limits the usefulness of the pullout test in troubleshooting problems suspected after placement is completed and the necessity of repairing the surface which is marred by a crater about 6 in. across. Commercial inserts have embedment depths on the order of 1 to 2 in. Since the vibrator operator may notice where the inserts are, the consolidation of concrete around them may not be representative of the entire member.

(4) Maturity method (ASTM C 1074 (CRD-C 70)). Assuming sufficient moisture is present, the rate of hydration of the cementitious materials in a concrete mixture is influenced by the concrete temperature. Therefore, the strength of concrete at any age is a function of its thermal history. The maturity method accounts for the combined effects of temperature and time on strength development. The concrete thermal history and a maturity function are used to calculate a maturity value which quantifies the combined effects of time and temperature. Concrete strength is expressed as a function of its maturity by means of a strength-maturity relationship. So, if samples of the same concrete are subjected to different curing temperatures, the strength-maturity relationship for that concrete and the thermal histories of the samples can be used to estimate their strengths. The strength-maturity relationship must be established for the concrete to be used in the structure in order to use the maturity method. ASTM C 1074 describes the procedure to be followed in developing this relationship using the concrete of interest. The temperature of history of the in-place concrete is continuously monitored, and from these data the in-place maturity is calculated. The in-place concrete strength can then be estimated at any point in time based upon the concrete maturity at that same time and the strength-maturity relationship. Commercial instruments are available which automatically compute concrete maturity; however, care should be exercised in their use since the maturity function used by the instrument may not be applicable to the concrete in the structure. To use the maturity method to estimate in-place concrete strength, there must be sufficient moisture for continued hydration, and the concrete in the structure must be the same as that used to develop the strength-maturity relationship. Proper curing assures the first condition will be met, and conducting slump, air content, unit weight, and accelerated strength tests on concrete representative of that going into the structure will assure the latter condition is met. The maturity method has obvious applications in the control of form stripping, shoring removal, and termination of cold-weather protection.

(5) Cores (ASTM C 42) (CRD-C 27). Coring is usually the method ultimately chosen to determine the in-place characteristics of concrete especially if the dispute involves payment to the Contractor or other problems such as the location of the member or the amount of reinforcement present. Planning for the core sampling and laying out the drill holes should follow (ASTM C 823 (CRD-C 26)). In heavily reinforced structures, it may be impossible to obtain a core sample from which compressive strength specimens may be taken since reinforcing steel may be so prevalent in the concrete that cores free of reinforcing steel and having height-to-diameter ratios equal to 1 or more cannot be obtained. It may be possible, however, to obtain specimens from such cores which will allow a determination of air-void system parameters (ASTM C 457 (CRD-C 42)) or analysis for the products of reactivity. Additionally, the effect of severing reinforcing steel on the integrity of the structure should be analyzed. If possible, the size of the core taken should be related to the nominal maximum size aggregate in the structure. If 37.5-mm (1-1/2-in.) maximum size aggregate is used in the structure then 6-in. cores should be drilled. In structures using larger aggregate, it may be practical to take cores up to 18 in. in diameter, but costs increase rapidly and the large core usually cannot be taken to a depth of more than 3 or 4 ft. Coring may prove expensive and the holes have to be backfilled, but the resulting data are usually accepted as the best evidence of the condition of the concrete in place.

(6) Pulse velocity method (ASTM C 597 (CRD-C 51)). This method involves the application of a mechanical impulse to a solid mass of material. The speed of the waves which are subsequently generated and which pass through the material are dependent on the elastic properties

of the material. The pulses can be generated either by a hammer blow or by an electroacoustic transducer. The pulse velocity method may be used to determine the uniformity of concrete. However, a number of factors affect pulse velocity measurements, including concrete moisture content and the presence of reinforcing steel. Reinforcing steel may be especially troublesome if it is oriented parallel to the pulse-propagation direction. The resulting apparent velocity through such a member will be greater than the actual velocity through the concrete. Failure to account for the presence and orientation of reinforcing steel may lead to inaccurate conclusions regarding the concrete quality. While pulse-velocity equipment is commercially available, its use and the interpretation of the pulse-velocity measurements requires special training and techniques.

(7) Other methods. Other methods in addition to those above are in the development stages. Contact WES for additional information.

9-4. Preplacement Quality Verification

The quality of all concrete placement areas should be verified prior to the actual placement of any concrete. For complicated placements, these quality verifications should be made as each element of the preparation for actual placement is completed. That is, foundation preparation, joint preparation, form installation, the placement of reinforcing bars, all embedded metal work, waterstops, conduits, mechanical piping, and cleanup should be verified for quality and checked out as each is completed. Other items that must be kept in mind at all times during all phases of this work are the provisions for safety and access to the placements, including all scaffolding, walkways, work platforms, ladders, and railings along with whatever weather protection and drainage provisions are required. If each element of this preparation is thoroughly verified as it is completed, it will then only require a cursory verification immediately prior to the concrete placement to be assured that the conditions have not changed. On a small or simple placement, the final quality verification may be all that is required prior to concrete placement. These preplacement verifications will be more systematic and accurate if a checklist is used. This checklist is to be initiated and dated by the representatives of the Contractor and the Government as each element in this preparation is completed. These checklists are known by various names, such as lift checkout cards and form checkout cards. The format of these checklists can vary according to the project requirements and the practice of the individual districts. All essential information is recorded. A separate form or checkout card is to be prepared for each concrete placement and retained in the Government's official project files. The Guide Specifications "Mass Concrete" (CW-03305) and "Cast-In-Place Structural Concrete" (CW-03301) also require the Contractor to provide a written report certifying that all elements of the placement are ready to receive concrete. While it has become the practice in some districts and divisions for the Contractor's representative and the Corps' quality assurance representative to jointly verify and sign the checkout card, it should be kept in mind that this is, in fact, the sole responsibility of the contractor and not be inferred as a joint responsibility. The advantage of a jointly signed card is that it establishes the means by which both the Corps' quality assurance representative and the contractor's quality control representative will be satisfied that the elements of the placement meet the project specification requirements before the concrete placement begins. Figure 7-1 is an example of a form checkout record.

9-5. Project Laboratory

a. General. A government field laboratory should be provided as close as possible to the mixing plant. The building housing the laboratory normally includes office space for the concrete personnel and facilities for filing the project concrete records.

b. Space requirements.

(1) Large-volume mass concrete project. At least 1,000 ft^2 of work space, exclusive of office space, should be provided for major mass concrete projects where it is expected that concrete will be placed on a continuous day-to-day basis throughout the construction season.

(2) Other. At least 500 ft^2 of work space, exclusive of office space, should be provided for moderate size projects.

c. Equipment.

(1) Large-volume mass concrete project. Storage tanks with a capacity of 300 cylinders and a 200,000-lbf compression testing machine, complying with requirements of ASTM C 39 (CRD-C 14), should be provided. New machines being purchased and older machines, returned to the manufacturer for repair, should be required to comply with the 1-percent accuracy requirement. Older machines, which are not under manufacturer's warranty and are presently in use, should be required to comply with a ± 3-percent accuracy requirement. Aggregate testing equipment should include that equipment necessary to perform tests for absorption, density, surface moisture, and sieve analysis. Heavy-duty laboratory screening equipment, such as the Gilson for coarse aggregate and the Ro-Tap for fine

aggregate, should be provided. Concrete testing equipment includes that equipment necessary for determining air content and slump and for molding test specimens. The laboratory should not include a concrete mixer.

(2) Other. Moderate size projects should include a curing tank with a capacity of 100 cylinders. If a compression testing machine is not available, cylinders may be shipped to either a division laboratory or large-volume project for testing. Aggregate and concrete testing equipment should be the same as for a large project. The laboratory facilities for a small project should be limited to equipment for measuring air content and slump and for molding test specimens. Curing of test cylinders and transportation to the laboratory for testing must be in strict accordance with ASTM C 31 (CRD-C 11).